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(54) **GRO-1, GENE DE L'HORLOGE DE C. ELEGANS**

(54) **THE C. ELEGANS CLOCK GENE GRO-1**

(57) L'invention concerne l'identification du gène gro-1 et dévoile le rôle joué par le gène gro-1 dans le contrôle d'une horloge physiologique centrale.

(57) The invention relates to the identification of gro-1 and to show that the gro-1 gene is involved in the control of a central physiological clock.

ABSTRACT OF THE INVENTION

The invention relates to the identification of *gro-1* and to show that the *gro-1* gene is involved in the control of a central physiological clock.

WHAT IS CLAIMED IS:

1. A *gro-1* gene which has a function at the level of cellular physiology involved in developmental rate and longevity, wherein *gro-1* is located within an operon and *gro-1* mutants have a longer life and a altered cellular metabolism relative to the wild-type.

2. A GRO-1 protein which has a function at the level of cellular physiology involved in developmental rate and longevity, wherein said GRO-1 protein is encoded by the gene of claim 1.

3. A method for the diagnosis and/or prognosis of cancer in a patient, which comprises the steps of:
a) obtaining a tissue sample from said patient;
b) analyzing DNA of the obtained tissue sample of step a) to determine if the human *gro-1* gene is altered, wherein alteration of the human *gro-1* gene is indicative of cancer.

4. A mouse model of aging and cancer, which comprises a gene knock-out of murine gene homologous to *gro-1* according to claim 1.

5. The use of compounds interfering with enzymatic activity of GRO-1 of claim 2 for enhancing longevity of a host.

6. The use of compounds interfering with enzymatic activity of GRO-1 of claim 2 for inhibiting of tumorous growth.

7. The use of *gro-1* of claim 1 to identify at least one other gene within or in the proximity of the

gro-1 operon, wherein said at least one other gene has a related function.

8. A *hap-1* gene which may have a function at the level of cellular physiology involved in developmental rate and longevity.

THE *C. ELEGANS* gro-1 GENE

BACKGROUND OF THE INVENTION

(a) Field of the Invention

The invention relates to the identification of *gro-1* and to show that the *gro-1* gene is involved in the control of a central physiological clock.

(b) Description of Prior Art

The *gro-1* gene was originally defined by a spontaneous mutation isolated from of a *Caenorhabditis elegans* strain that had recently been established from a wild isolate (J. Hodgkin and T. Doniach, *Genetics* **146**: 149-164 (1997)). We have shown that the activity of the *gro-1* gene controls how fast the worms live and how soon they die. The time taken to progress through embryonic and post-embryonic development, as well as the life span of *gro-1* mutants is increased (Lakowski and Hekimi, *Science* **272**:1010-1013, (1996)). Furthermore, these defects are maternally rescuable: when homozygous mutants (*gro-1/gro-1*) derive from a heterozygous mother (*gro-1/+*), these animals appear to be phenotypically wild-type. The defects are seen only when homozygous mutants derive from a homozygous mother (Lakowski and Hekimi, *Science* **272**:1010-1013, (1996)). In general, the properties of the *gro-1* gene are similar to those of three other genes, *clk-1*, *clk-2* and *clk-3* (Wong *et al.*, *Genetics* **139**: 1247-1259 (1995); Hekimi *et al.*, *Genetics*, **141**: 1351-1367 (1995); Lakowski and Hekimi, *Science* **272**:1010-1013, (1996)), and this combination of phenotypes has been called the Clk ("clock") phenotype. All four of these genes interact to determine developmental rate and longevity in the nematode. Detailed examination of the *clk-1* mutant phenotype has led to the suggestion that there exists a central physiological clock which coordinates

all or many aspects of cellular physiology, from cell division and growth to aging. All four genes have a similar phenotype and thus appear to impinge on this physiological clock.

It would be highly desirable to be provided with the molecular identity of the *gro-1* gene.

SUMMARY OF THE INVENTION

One aim of the present invention is to provide the molecular identity of the *gro-1* gene.

In accordance with the present invention there is provided a *gro-1* gene which has a function at the level of cellular physiology involved in developmental rate and longevity, wherein *gro-1* is located within an operon and *gro-1* mutants have a longer life and a altered cellular metabolism relative to the wild-type.

In accordance with the present invention there is also provided a GRO-1 protein which has a function at the level of cellular physiology involved in develop-mental rate and longevity, wherein said GRO-1 protein is encoded by the *gro-1* gene identified above.

In accordance with the present invention there is also provided a method for the diagnosis and/or prognosis of cancer in a patient, which comprises the steps of:

a) obtaining a tissue sample from said patient;

b) analyzing DNA of the obtained tissue sample of step a) to determine if the human *gro-1* gene is altered, wherein alteration of the human *gro-1* gene is indicative of cancer.

In accordance with the present invention there is also provided a mouse model of aging and cancer, which comprises a gene knock-out of murine gene homologous to *gro-1*.

In accordance with the present invention there is provided the use of compounds interfering with enzy-

matic activity of GRO-1 for enhancing longevity of a host.

In accordance with the present invention there is provided the use of compounds interfering with enzymatic activity of GRO-1 for inhibiting of tumorous growth.

In accordance with the present invention there is provided the use of *gro-1* to identify at least one other gene within or in the proximity of the *gro-1* operon.

In accordance with the present invention there is provided a *hap-1* gene which may have a function at the level of cellular physiology involved in developmental rate and longevity.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A illustrates the genetic mapping of *gro-1*;

Fig. 1B illustrates the physical map of the *gro-1* region;

Fig. 2A illustrates cosmid clones able to rescue the *gro-1 (e2400)* mutant phenotype;

Fig. 2B illustrates the genes predicted by Genefinder, the relevant restriction sites and the fragments used to subclone the region;

Fig. 3A illustrates the genomic sequence and translation of the *C. elegans gro-1* gene;

Fig. 3B illustrates the predicted mutant protein;

Fig. 4 illustrates the five genes of the *gro-1* operon;

Fig. 5 illustrates the alignment of the predicted GRO-1 amino acid sequence with homologues from other species (see text for the origin of these sequences);

Fig. 6 illustrates the biosynthetic step catalyzed by DMAPP transferase (MiaAp in *E. coli*, Mod5p in *S. cerevisiae*, and GRO-1 in *C. elegans*); and

Fig. 7 illustrates the alignment of the predicted HAP-1 amino acid sequence with homologues from other species.

DETAILED DESCRIPTION OF THE INVENTION

The *gro-1* phenotype

In addition to the previously documented phenotypes, we recently found that *gro-1* mutants were temperature-sensitive for fertility. At 25°C the progeny of these mutants is reduced so much that a viable strain cannot be propagated. In contrast, *gro-1* strains can easily be propagated at 15 and 20°C.

We also discovered that the *gro-1(e2400)* mutation increases the incidence of spontaneous mutations. As *gro-1(e2400)* was originally identified in a non-standard background (Hodgkin and Doniach, *Genetics* **146**: 149-164 (1997)), we first backcrossed the mutations 8 times against N2, the standard wild type strain. We then undertook to examine the *gro-1* strain and N2 for the occurrence of spontaneous mutants which could be identified visually. We focused on the two class of mutants which are detected the most easily by simple visual inspection, uncoordinated mutants (Unc) and dumpy mutants (Dpy). We examined 8200 wild type worms and found no spontaneous visible mutant. By contrast, we found 6 spontaneous mutants among 12500 *gro-1* mutants examined. All mutants produced entirely mutant progeny indicating that they were homozygous.

Positional cloning of *gro-1*

gro-1 lies on linkage group III, very close to the gene *clk-1*. To genetically order *gro-1* with respect to *clk-1* on the genetic map, 54 recombinants in

the *dpy-17* to *lon-1* interval were selected from among the self progeny of a strain which was *unc-79(e1030) + + clk-1(e2519) lon-1(e678) +/+ dpy-17(e164) gro-1(e2400) + sma-4(e729)*. Three of these showed neither the Gro-1 nor the Clk-1 phenotypes, but carried *unc-79* and *sma-4*, indicating that these recombination events had occurred between *gro-1* and *clk-1*. From the disposition of the markers, this showed that the gene order was *dpy-17 gro-1 clk-1 lon-1*, and the frequency of events indicated that the *gro-1* to *clk-1* distance was 0.03 map units. In this region of the genome, this corresponds to a physical map distance of ~20 kb.

Several cosmids containing wild-type DNA spanning this region of the genome were tested by microinjection into *gro-1* mutants for their ability to complement the *gro-1(e2400)* mutation (Fig. 1). *gro-1* was mapped between *dpy-17* and *lon-1* on the third chromosome, 0.03 m.u. to the left of *clk-1* (Fig. 1A).

Based on the above genetic mapping, *gro-1* was estimated to be approximately 20 kb to the left of *clk-1*. Eight cosmids (represented by medium bold lines) were selected as candidates for transformation rescue (Fig. 1B). Those which were capable of rescuing the *gro-1(e2400)* mutant phenotype are represented as heavy bold lines (Fig. 1B).

Of these, only B0498, C34E10 and ZC395 were able to rescue the mutant phenotype. Transgenic animals were fully rescued for developmental speed. In addition, the transgenic DNA was able to recapitulate the maternal rescue seen with the wild-type gene, that is, mutants not carrying the transgenic DNA but derived from transgenic mothers display a wild type phenotype. The 7 kb region common to the three rescuing cosmids had been completely sequenced, and this sequence was publicly available.

We generated subclones of ZC395 and assayed them for rescue (Fig. 2A). The common 6.5 kb region is blown up in part B. B0498 has not been sequenced and therefore its ends can not be positioned and are therefore represented by arrows.

One subclone pMQ2, spanned 3.9 kb and was also able to completely rescue the growth rate defect and recapitulate the maternal effect. The sequences in pMQ2 potentially encodes two genes. However, a second subclone, pMQ3, which contained only the first of the potential genes (named ZC395.7 in Fig. 2A), was unable to rescue.

Furthermore, frameshifts which would disrupt each of the two genes' coding sequences were constructed in pMQ2 and tested for rescue. Disruption of the first gene (in pMQ4) did not eliminate rescuing ability, but disruption of the second gene (in pMQ5) did. This indicates that the *gro-1* rescuing activity is provided by the second predicted gene.

pMQ2 was generated by deleting a 29.9 kb *Spe*I fragment from ZC395, leaving the left-most 3.9 kb region containing the predicted genes ZC395.7 and ZC395.6 (Fig. 2B). pMQ3 was created in the same fashion, by deleting a 31.4 kb *Nde*I fragment from ZC395, leaving only ZC395.7 intact. In pMQ4, a frameshift was induced in ZC395.7 by degrading the 4 bp overhang of the *Apa*I site. A frameshift was also induced in pMQ5 by filling in the 2 bp overhang of the *Nde*I site found in the second exon of ZC395.6. These frameshifts presumably abolish any function of ZC395.7 and ZC395.6 respectively. The dotted lines represent the extent of frameshift that resulted from these alterations.

To establish the splicing pattern of this gene, cDNAs encompassing the 5' and 3' halves of the gene

were produced by reverse transcription-PCR and sequenced (Fig. 3).

This revealed that the gene is composed of 9 exons, spans ~2 kb, and produces an mRNA of 1.3 kb. To confirm that this is indeed the *gro-1* gene, genomic DNA was amplified by PCR from a strain containing the *gro-1(e2400)* mutation and the amplified product was sequenced. A lesion was found in the 5th exon, where a 9 base-pair sequence has been replaced by a 2 base-pair insertion, leading to a frameshift (Fig. 3B). Fig. 3B illustrates those residues which differ from wild type are in bold.

The reading frame continues out-of-frame for another 33 residues before terminating.

Fig. 3A illustrates the coding sequence in capital letters, while the introns, and the untranslated and intergenic sequence are in lower case letters. The protein sequence is shown underneath the coding sequence. Position 1 of the nucleotide sequence is the first base after the SL2 *trans*-splice acceptor sequence. Position 1 of the protein sequence is the initiator methionine. All PCR primers used for genomic and cDNA amplification are represented by arrows. For primers extending downstream (arrows pointing right) the primer sequence corresponds exactly to the nucleotides over which the arrow extends. But for primers extending upstream (arrows pointing left) the primer sequence is actually the complement of the sequence under the arrow. In both cases the arrow head is at the 3' end of the primer. The sequence of the two primers which flank *gro-1* (SHP93 and SHP92) are not represented in this figure. Their sequences are: SHP93 TTTCTGGATTTTAACCTTCC and SHP92 GATAGTTCCCTTCGTTCGGG. The wild type splicing pattern was determined by sequencing of the cDNA. Identification of the *e2400*

lesion was accomplished by sequencing the *e2400* allele. The *e2400* lesion consists of a 9 bp deletion and a 2 bp insertion at position 1196, resulting in a frameshift.

gro-1 is part of a complex operon

Amplification of the 5' end of *gro-1* from cDNA occurred only when the *trans*-spliced leader SL2 was used as the 5' primer, and not when SL1 was used. SL2 is used for *trans*-splicing to the downstream gene when two genes are organized into an operon (Spieth *et al.*, *Cell* **73**: 521-532 (1993); Zorio et al., *Nature* **372**: 270-272 (1994)). This indicates that at least one gene upstream of *gro-1* is co-transcribed with *gro-1* from a common promoter. We found that sequences from the 5' end of the three next predicted genes upstream of *gro-1* (ZC395.7, C34E10.1, and C34E10.2) all could only be amplified with SL2. Sequences from the fourth predicted upstream gene (C34E10.3), however, could be amplified with neither spliced leader, suggesting that it is not *trans*-spliced. The distance between genes in operons appear to have an upper limit (Spieth *et al.*, *Cell* **73**: 521-532 (1993); Zorio et al., *Nature* **372**: 270-272 (1994)), and no gene is predicted to be close enough upstream of C34E10.3 or downstream of *gro-1* to be co-transcribed with these genes. Our findings suggest therefore that *gro-1* is the last gene in an operon of five co-transcribed genes (Fig. 4).

Nested PCR was used to amplify the 5' end of each gene. SL1 or SL2 specific primers were used in conjunction with a pair of gene-specific primers. cDNA generated by RT-PCR using mixed stage N2 RNA was used as template in the nested PCR. Fig. 4A illustrates a schematic of the *gro-1* operon showing the coding sequences of each gene and the primers (represented by flags) used to establish the *trans*-splicing patterns.

Fig. 4B illustrates the products of the PCR with SL1 and SL2 specific primers for each of the five genes. The sequences of the primers used are as follows: SL1: TTTAATTACCCAAGTTTGAG, SL2: TTTTAACCCAGTTACTCAAG, SHP141: AAAACTTCTACCAACAATGG, SHP142: CGTAATCTCTCTCGATTAGC, SHP143: CCGTGGGATGGCTACTTGCC, SHP144: TGGATTTGTGGCACGAGCGG, SHP145: TTGATTGCCTCTCCTCGTCC, SHP146: ATCAACATCTGATTGATTCC, SHP130: CATCCAAAAGCAGTATCACC, SHP119: ACATCTTTATCCATTTCTCC, SHP95: TACAGGAATTTTTGAACGGG, SHP99: ATCGATACCACCGTCTCTGG.

The gene immediately upstream of *gro-1*, has homology to the yeast gene *HAM1*, and we have renamed the gene *hap-1*. We have established its splicing pattern by reverse transcription PCR and sequencing. This revealed that *hap-1* is composed of 5 exons and produces an mRNA of 0.9 kb. We also found that sequences which were predicted to belong to ZC395.7 (now *hap-1*) are in fact spliced to the exons of C34E10.1. This is consistent with our finding that *hap-1* is SL2 spliced as it puts the end of the C34E10.1 very close to the start of *hap-1* (Fig. 4).

The *gro-1* gene product

Conceptual translation of the *gro-1* transcript indicated that it encodes a protein of 430 amino acids highly similar to strongly conserved cellular enzyme: dimethylallyldiphosphate:tRNA dimethylallyltransferase (DMAPP transferase). Fig. 5 shows an alignment of *gro-1* with the published sequences of the *E. coli* (Caillet and Droogmans, *J. Bactriol.* 70: 4147-52 (1988)) and yeast (Najarian *et al.*, *Molecular & Cellular Biology* **7**:185-91 (1987)) enzymes, as well as with a sequence inferred from a human expressed sequence tag (Genbank ID: Z40724). The human clone has been used to derive a sequence tagged site (STS). This means that the

genetic and physical position of the human *gro-1* homologue is known. It maps to chromosome 1, 122.8 cR from the top of Chr 1 linkage group and between the markers D1S255 and D1S2861. This information was found in the UniGene database or the National Center for Biotechnology Information (NCBI). Fig. 5 illustrates residues where the biochemical character of the amino acid is conserved are shown in bold. Identical amino acids are indicated further with a dot. The ATP/GTP binding site and the C2H2 zinc finger site are predicted and not experimental. The zinc finger site occurs only in the worm sequence. The point at which the *gro-1(e2400)* mutation alters the reading frame of the sequence is shown. The two alternative initiator methionines in the yeast sequence, and the putative corresponding methionines in the worm sequence, are underlined.

Additional homologue can be found for *Leishmania major* (Genbank accession T93363) and *Arabidopsis thaliana* (Genbank accession B09117). In *E. coli* and other bacteria, the gene encoding DMAPP transferase is called *miaA* (a.k.a *trpX*) and is called *mod5* in yeast. DMAPP transferase catalyzes the modification of adenosine 37 of tRNAs whose anticodon begins with U (Fig. 6).

In these organisms the enzyme has been shown to use dimethylallyldiphosphate as a donor to generate dimethylallyl-adenosine (dma^6A37), one base 3' to the anticodon (for review and biochemical characterization of the bacterial enzyme see Persson *et al., Biochimie* **76:** 1152-1160 (1994); Leung et *al., J Biol Chem* **272:** 13073-13083 (1997); Moore and Poulter, *Biochemistry* **36:**604-614 (1997)). In earlier literature this modification is often referred to as isopentenyl adenosine (i^6A37).

The high degree of conservation of the protein sequence between GRO-1 and DMAPP in *S. cerevisiae* and *E. coli* suggest that GRO-1 possesses the same enzymatic activity as the previously characterized genes. The sequence contains a number of conserved structural motifs (Fig. 5), including a region with an ATP/GTP binding motif which is generally referred to as the 'A' consensus sequence (Walker *et al., EMBO J* **1:** 945-951 (1982)) or the 'P-loop' (Saraste *et al., Trends Biochem Sci* **15:** 430-434 (1990)).

In addition, at the C-terminal end of the GRO-1 sequence, there is a C2H2 zinc finger motif as defined by the PROSITE database. This type of DNA-binding motif is believed to bind nucleic acids (Klug and Rhodes, *Trends Biochem Sci* **12:** 464-469 (1987)). Although there appears to be some conservation between the worm and yeast sequences in the C-terminus end of the protein (Fig. 5), including in the region encompassing the zinc finger in GRO-1, the zinc finger motif *per se* is not conserved in yeast.

In yeast DMAPP transferase is the product of the *MOD5* gene, and exists in two forms: one form which is targeted principally to the mitochondria, and one form which is found in the cytoplasm and nucleus. These two forms differ only by a short N-terminal sequence whose presence or absence is determined by differential translation initiation at two "in frame" ATG codons. (Gillman *et al., Mol & Cell Biol* **11:** 2382-90 (1991)). The *gro-1* open reading frame also contains two ATG codons at comparable positions, with the coding sequence between the two codons constituting a plausible mitochondrial sorting signal (Figs. 3 and 5). It is likely therefore that DMAPP transferase in worms also exists in two forms, mitochondrial and cytoplasmic.

The *hap-1* gene product

hap-1 is homologous to the yeast gene *HAM1* as well as to sequences in many organisms including bacteria and mammals (Fig. 7).

The origin of the worm and yeast sequence is as described above and below. The human sequence was inferred from a cDNA sequence assembled from expressed sequence tags (ESTs); the accession numbers of the sequences used were: AA024489, AA024794, AA025334, AA026396, AA026452, AA026502, AA026503, AA026611, AA026723, AA035035, AA035523, AA047591, AA047599, AA056452, AA115232, AA115352, AA129022, AA129023, AA159841, AA160353, AA204926, AA226949, AA227197 and D20115. The *E. coli* sequence is a predicted gene (accession 1723866).

Mutations in *HAM1* increase the sensitivity of yeast to the mutagenic compound 6-N-hydroxylaminopurine (HAP), but do not increase spontaneous mutation frequency (Nostov *et al., Yeast* **12**:17-29 (1996)). HAP is an analog of adenine and *in vitro* experiments suggest that the mechanism of HAP mutagenesis is its conversion to a deoxynucleoside triphosphate which is incorporated ambiguously for dATP and dGTP during DNA replication (Abdul-Masih and Bessman, *J Biol Chem* **261 (5)**: 2020-2026 (1986)). The role of the Hamlp gene product in increasing sensitivity to HAP remains unclear.

Explaining the pleiotropy of *miaA* and *gro-1*

Mutations in *miaA*, the bacterial homologue of *gro-1*, show multiple phenotypes and affect cellular growth in complex ways. For example, in *Salmonella typhimurium*, such mutations result in 1) a decreased efficacy of suppression by some suppressor tRNA, 2) a slowing of ribosomal translation, 3) slow growth under various nutritional conditions, 4) altered regulation of several amino acid biosynthetic operons, 5) sensitivity to chemical oxidants and 6) temperature sensitivity for aerobic growth (Ericson and Björk, *J. Bacteriol.* **166:** 1013-1021 (1986); Blum, *J. Bacteriol.* **170:** 5125-5133 (1988)). Thus, MiaAp appears to be important in the regulation of multiple parallel processes of cellular physiology. Although we have not yet explored the cellular physiology of *gro-1* mutants along the lines which have been pursued in bacteria, the apparently central role of *miaA* is consistent with our findings that *gro-1*, and the other genes with a Clk phenotype, regulate many disparate physiological and metabolic processes in *C. elegans* (Wong et al., *Genetics* **139:** 1247-1259 (1995) ; Lakowski and Hekimi, *Science* **272:** 1010-1013 (1996); Ewbank et *al.*, *Science* **275:** 980-983 (1997)).

In addition to the various phenotypes discussed above, *miaA* mutations increase the frequency of spontaneous mutations (Connolly and Winkler, *J Bacteriol* **173(5):**1711-21 (1991); Connolly and Winkler, *J Bacteriol* **171:** 3233-46 (1989)). As described in the previous section we have preliminary evidence that *gro-1(e2400)* also increases the frequency of spontaneous mutations in worms.

How can the alteration in the function of MDAPP transferase result in so many distinct phenotypes? Bacterial geneticists working with *miaA* have generally

suggested that this enzyme and the tRNA modification it catalyzes have a regulatory function which is mediated through attenuation (e.g. Ericson and Björk, *J. Bacteriol.* **166:** 1013-1021 (1986)). Attenuation is a phenomenon by which the transcription of a gene is interrupted depending on the rate at which ribosomes can translate the nascent transcript. Ribosomal translation is slowed in *miaA* mutants, and thus, through an effect on attenuation, could affect the expression of many genes whose expression is regulated by attenuation.

gro-1(e2400) also produces pleiotropic effects and, in addition, displays a maternal-effect, suggesting that it is involved in a regulatory process (Wong *et al.*, *Genetics* **139:** 1247-1259 (1995). However, attenuation involves the co-transcriptional translation of nascent transcripts, which is not possible in eukaryotic cells were transcription and translation are spatially separated by the nuclear membrane. If the basis of the pleiotropy in *miaA* and *gro-1* is the same, then a mechanism distinct from attenuation has to be involved. Below we argue that this mechanism could be the modification by DMAPP transferase of adenine residues in DNA in addition to modification of tRNAs.

A role for *gro-1* in DNA modification?

We observed that *gro-1* can be rescued by a maternal effect, so that adult worms homozygous for the mutation, but issued from mother carrying one wild type copy of the gene display a wild type phenotype, in spite of the fact that such adults are up to 1000 fold larger than the egg produced by their mother. It is unlikely that enough wild type product can be deposited by the mother in the egg to rescue a adult which is 1000 times larger. This observation suggests therefore that *gro-1* can induce an epigenetic state which is not

altered by subsequent somatic growth. One of the best documented epigenetic mechanisms is imprinting in mammals (Lalande, *Annu Rev Genet* **30:** 173-196 (1996)) which is believed to rely on the differential methylation of genes (Laird and Jaenisch, *Annu Rev Genet* **30:** 441-464; Klein and Costa, Mutat Res **386:** 103-105 (1997)). Modification of bases in DNA have also been linked to regulation of gene expression in the protozoan *Trypanosoma brucei*. The presence of beta-D-glucosyl-hydroxymethyluracil in the long telomeric repeats of *T. brucei* correlates with the repression of surface antigen gene expression (Gommers-Ampt *et al.*, *Cell* **75:** 112-1136 (1993); van Leeuwen *et al.*, *Nucleic Acids Res* **24:** 2476-2482 (1996)).

gro-1 and *miaA* increase the rate of spontaneous mutations, which is generally suggestive of a role in DNA metabolism, and can be related to the observation that methylation is linked to spontaneous mutagenesis, genome instability, and cancer (Jones and Gonzalgo, *Proc. Natl. Acad. Sci. USA,* **94:** 2103-2105 (1997)).

Does *gro-1* have access to DNA? Studies with *mod5*, the yeast homologue of *gro-1*, have shown that one form of Mod5p is localized to the nucleus as well as to the cytoplasm (Boguta *et al.*, *Mol. Cell. Biol.* **14:** 2298-2306 (1994)), and this in spite of the fact that the tRNA modification is believed to occur exclusively in the cytoplasm (reviewed in Boguta *et al.*, *Mol. Cell. Biol.* **14:** 2298-2306 (1994)). Furthermore, studies of a gene *maf1* have shown that when *mod5* is mislocalized to the nucleus, the efficiency of certain suppressor tRNA is decreased, an effect known to be linked to the absence of the tRNA modification (Murawski *et al.*, *Acta Biochim. Pol.* **41:** 441-448 (1994)). Finally, as described in the previous section, *gro-1* contains a zinc finger, a nuclei acid binding motif. The zinc

finger could bind tRNAs, but as it is in the C-terminal domain of *gro-1* which has no equivalent in *miaA*, it is clearly not necessary for the basic enzymatic function. We speculate that it might be necessary to increase the specificity of DNA binding in the large metazoan genome.

miaA and *gro-1* are found in complex operons

We have found that *gro-1* is part of a complex operon of five genes (Fig. 4). It is believed that genes are regulated coordinately by single promoters when they participate in a common function (Spieth *et al.*, *Cell* **73**: 521-532 (1993)). In some cases, this is well documented. For example, the proteins LIN-15A and LIN-15B which are both required for vulva formation in *C. elegans*, are unrelated products from two genes transcribed in a common operon (Huang et al., *Mol Biol Cell* **5(4)**: 395-411 (1994)). One of the genes in the *gro-1* promoter is *hap-1*, whose yeast homologue has been shown to be involved in the control of mutagenesis (Nostov *et al.*, *Yeast* **12**: 17-29 (1996)). Under the hypothesis that *gro-1* modifies DNA, it suggest an involvement of *hap-1* in this or similar processes. The presence in the same operon also suggest that all five genes might collaborate in a common function. The phenotype of *gro-1* suggests that this function is regulatory. In this context, it should be noted that *miaA* also is part of a particularly complex operon (Tsui and Winkler, Biochimie **76**: 1168-1177 (1994)), although, except for *miaA/gro-1*, there are no other homologous genes in the two operons.

A role for *gro-1* in a central mechanism of physiological coordination

We have speculated that the genes with a Clk phenotype might participate in a central mechanism of physiological coordination, probably including the

regulation of energy metabolism. *clk-1* encodes a protein potentially involved in a diversity of processes, one of which being the regulation of the biosynthesis of ubiquinone (Ewbank et *al.*, *Science* **275:** 980-983 (1997)). Ubiquinone, also called coenzyme Q, is central to the production of ATP in mitochondria. How might *gro-1* fit into this picture?

One link is that dimethylallyldiphosphate is known to be the precursor of the lipid side-chain of ubiquinone. In bacteria, ubiquinone is the major lipid made from DMAPP. In eukaryotes cholesterol and its derivatives are also made from DMAPP. Interestingly, *C. elegans* requires cholesterol in the growth medium for optimal growth. This link, however, remains tenuous, in particular in the absence of an understanding of the biochemical function of CLK-1.

In several bacteria, the adenosine modification carried out by DMAPP transferase is only the first step in a series of further modification of this base (Persson *et al.*, *Biochimie* **76:** 1152-1160 (1994)). These additional modifications have been proposed to play the role of a sensor for the metabolic state of the cell (Buck and Ames, *Cell* **36:** 523-531 (1984); Persson and Björk, *J. Bacteriol.* **175:** 7776-7785 (1993)). For example, one of the subsequent steps, the synthesis of 2-methylthio-cis-ribozeatin is carried out by a hydroxylase encoded by the gene *miaE*. When the cells lack *miaE* they become incapable of using intermediates of the citric acid cycle such as fumarate and malate as the sole carbon source.

Another link to energy metabolism springs from the recent biochemical observations of Winkler and coworkers using purified DMAPP transferase (*E. coli* MiaAp) (Leung *et al.*, *J Biol Chem* **272:** 13073-13083 (1997)). These investigators observed that the enzyme

in competitively inhibited by phosphate nucleotides such as ATP or GTP. Furthermore, using their estimation of K_m of the enzyme and its concentration in the cell, they calculate that the level of inhibition of the enzyme *in vivo*, would exactly allow the enzyme to modify all tRNAs but any further inhibition would leave unmodified tRNAs. This suggests that the exact level of modification of tRNA (or of DNA) could be exquisitely sensitive to the level of phosphate nucleotides. Superficially, this is consistent with the phenotypic observations. The state of mutant cells which lack DMAPP transferase entirely would be equivalent of cells where very high levels of ATP would completely inhibit the enzyme. Such cells might therefore turn down the ATP generating processes in response to the signal provided by undermodified tRNAs (or DNA).

While the invention has been described in connection with specific embodiments thereof, it will be understood that it is capable of further modifications and this application is intended to cover any variations, uses, or adaptations of the invention following, in general, the principles of the invention and including such departures from the present disclosure as come within known or customary practice within the art to which the invention pertains and as may be applied to the essential features hereinbefore set forth, and as follows in the scope of the appended claims.

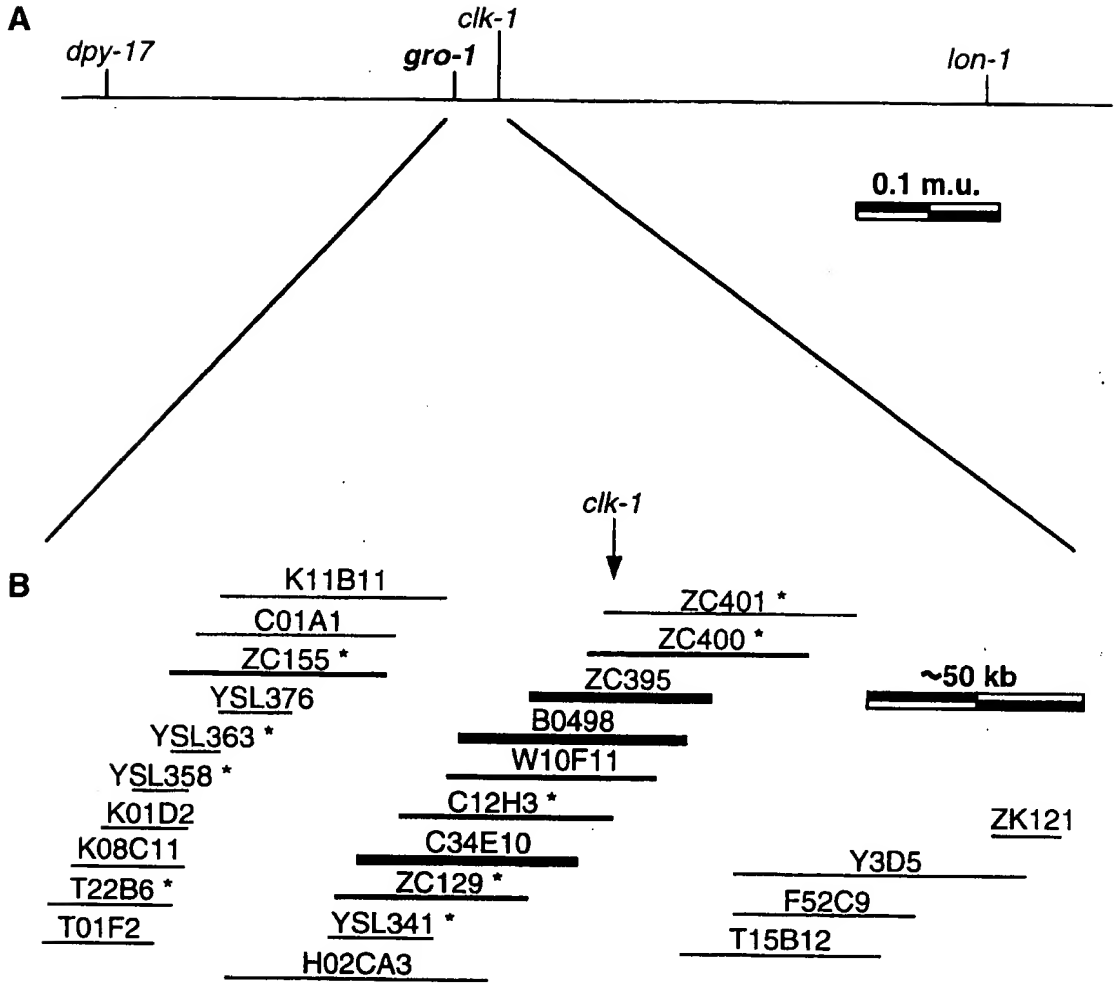
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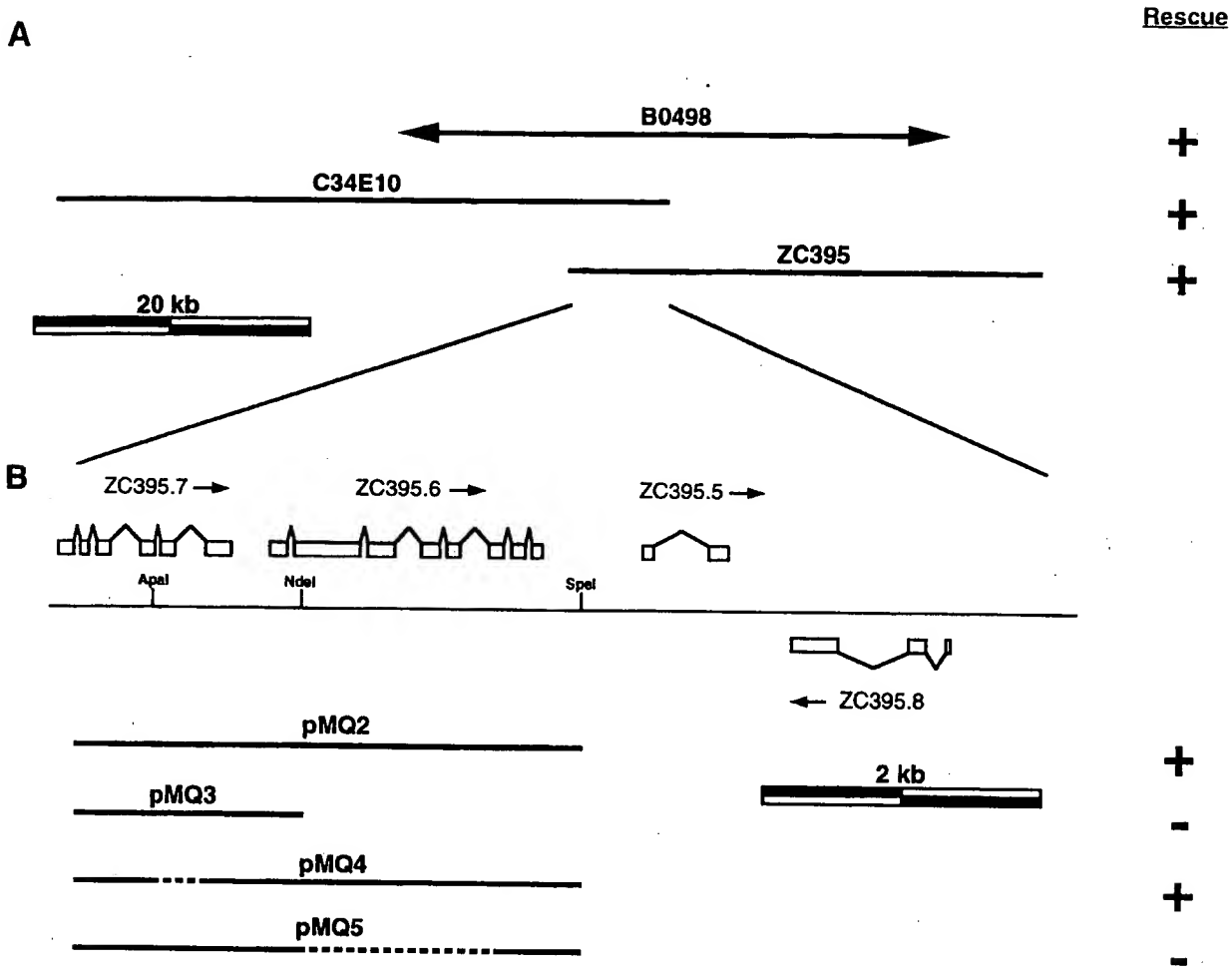
Fig. 1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+
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+
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+
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Fig. 2

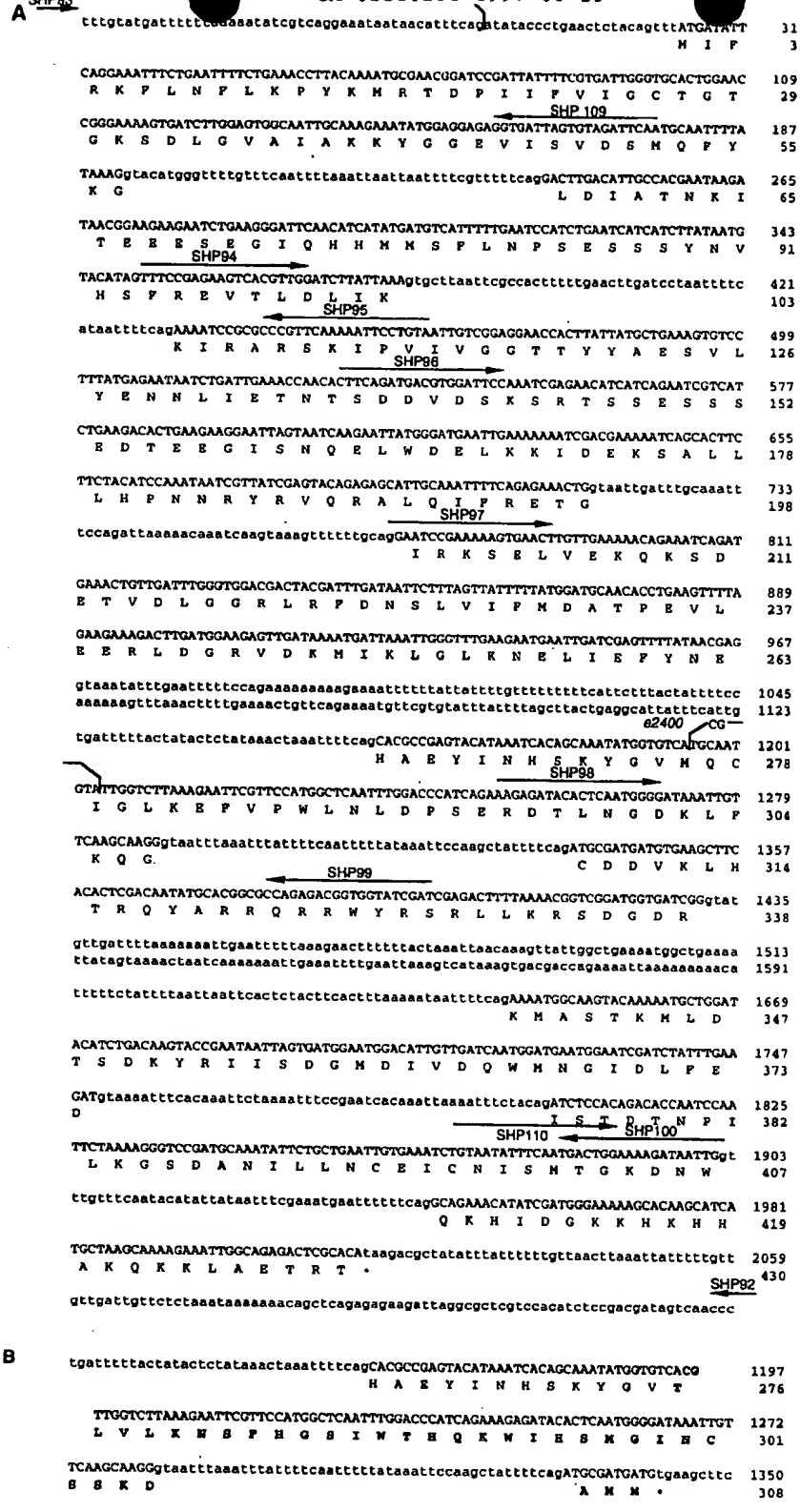
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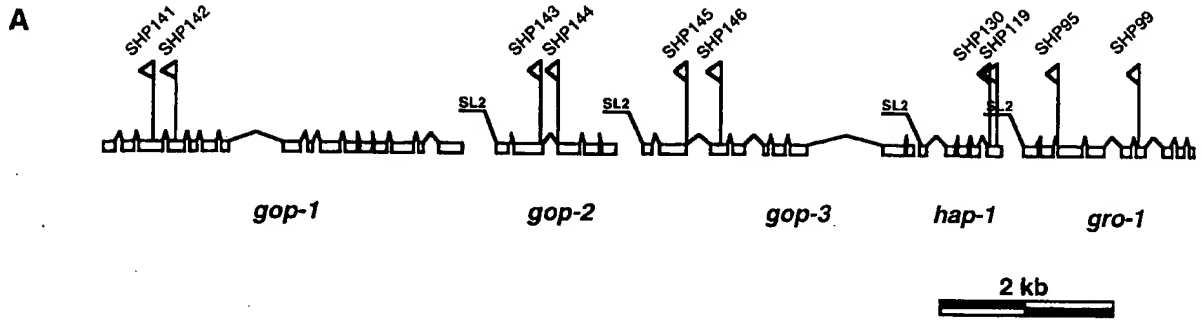
Fig. 3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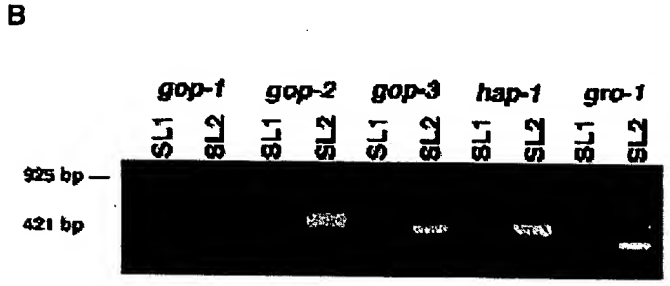
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SL1
SL2
925 bp
421 bp

Fig. 4

Sequence of GRO-1 and its homologues

```
                                                 .  .  ..  .          .    ..   .    .  .  .    .     .
H.sapiens                                  RTLPLVVILGATGTXKSTLALQLGQRLGGEIVSADSMQVYEGLDIITNKVSAQEQRIXRH
C.elegans          1 MIFRKFLNFLKPYKMRTDPIIFVIGCTGTGKSDLGVAIAKKYGGEVISVDSMQFYKGLDIATNKITEEESEGIQH
S.cerevisiae       1     MLKGPLKGCLNMSKKVIVIAGTTGVGKSQLSIQLAQKFNGEVINSDSMQVYKDIPIITNKHPLQEREGIPH
E.coli             1         MSDISKASLPKAIFLMGPTASGKTALAIELRKILPVELISVDSALIYKGMDIGTAKPNAEELLAAPH
                                                  ATP/GTP
                                                 binding site

H.sapiens         61 HMISFVDP.    .    .          .    ..  ....  .
C.elegans         76 HMMSFLNPSESSSSYNVHSFREVTLDLIKKIRARSKIPVIVGGTTYYAESVLYENNLIETNTSDDVDSKSRTSSES
S.cerevisiae      72 HVMNHVDWSE--EYYSHRFETECMNAIEDIHRRGKIPIVVGGTHYYLQTLFNKRVDTKSSERKLTRKQLDILEST
E.coli            68 RLLDIRDPSQ--AYSAADFRRDALAEMADITAAGRIPLLVGGTMLYFKALLEGLSPLPSADPEVRARIEQQAAEQ

                                  .  .  .  ...  .  .  .     .  .                    .
C.elegans        151 SSEDTEEGISNQELWDELKKIDEKSALLLHPNNRYRVQRALQIFRETGIRKSELVEKQKSDETVDLGGRLRFDNS
S.cerevisiae     147 DPDV---------IYNTLVKCDPDIATKYHPNDYRRVQRMLEIYYKTGKKPSETFNEQK--------ITLKFD-T
E.coli           143 GWES---------LHRQLQEVDPVAAARIHPNDPQRLSRALEVFFISGKTLTELTQTSG--------DALPYQVH

                                                                          e2400
                                 .  .  .  .  .  .  .                      |
C.elegans        226 LVIFMDATPEVLEERLDGRVDKMIKLGLKNELIEFYNEHAEYINHSKYGVMQCIGLKEFVPWLNLDPSERDTLNG
S.cerevisiae     205 LFLWLYSKPEPLFQRLDDRVDDMLERGALQEIKQLYEYYSQNKFTPEQCENGVWQVIGFKEFLPWLTGKTDDNTV
E.coli           202 QFAIAPASRELLHQRIEQRFHQMLASGFEAEVRALFARGDLHTDLPSIRCVGYRQMWSYLEGEISYDEMVYRGVC

                                     ...  .  ..  .                                        .
C.elegans        301 DKLFKQGCDDVKLHTRQYARRQRRWYRSRLLKRSDGDRKMASTKMLDTSDKYRIISDGMDIVDQWMNGIDLFEDI
S.cerevisiae     280 KLEDCIERMKT--RTRQYAKRQVKWIKKMLIPDIKGDILLDATDLSQWDTNASQRAIAISNDFISNRPIKQERAP
E.coli           277 -------------ATRQLAKRQITWLRGWEGVHWLDSEKPEQARDEVLQVVGAIAG

                                  ..      .   C2H2 zinc finger  .
C.elegans        376 STDTNPILKGSDANILLNCEICNISMTGKDNWQKHIDGKKHKHHAKQKKLATRT
S.cerevisiae     353 KALEELLSKGETTMKKLDDWTHYTRNVCRNADGKNVVAIGEKYWKIHLGSRRHKSNLKRNTRQADFEKWKINKKETVE
                                                                          .
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Fig. 5

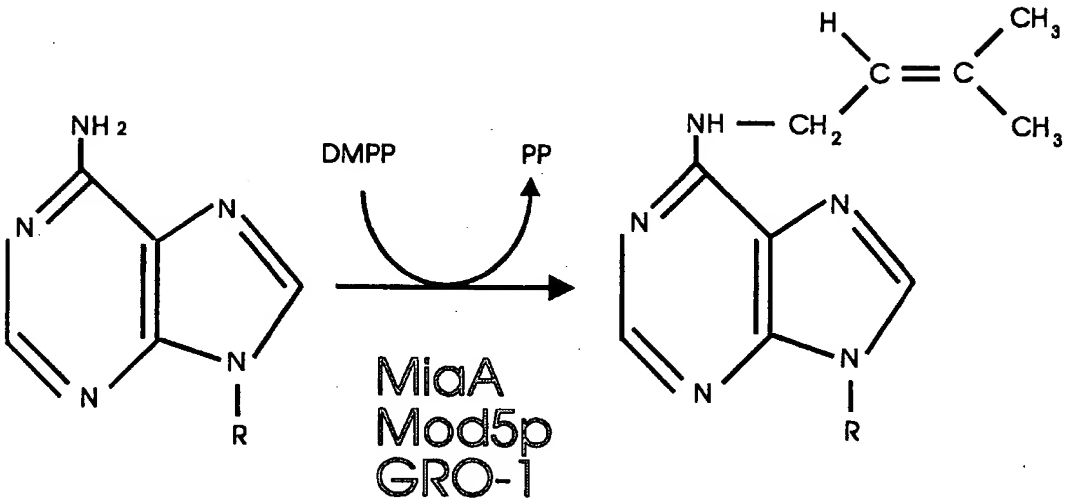

Fig. 6

Sequence of HAP-1 and its homologues

```
H. sapiens              MAASLVGKKIVFVTGNAKKLEEVVQILGDKFP-----CTLVAQKIDLPEYXG-EPDEISIQKCQE
C. elegans      MLYILWKLNYLQKKMSLRKINFVTGNVKKLEEVKAILKNFE--------VSNVDVDLDEFQG-EPEFIAERKCRE
S. cerevisiae                 MSNNEIVFVTGNANKLKEVQSILTQEVDNNNKTIHLINEALDLEELQDTDLNAIALAKGKQ
E. coli                          MQKVVLATGNVGKVRELASLLSDFGLD-----IVAQTDLGVDSAEETGLTFIENAILKA

H. sapiens      AVRQV-QG-PVLVEDTCLCFNALGXLPGPYIKWFL--EKLKPEGLHQLLAGFED-----KSAYALCTFALSTGDP
C. elegans      AVEAV-KG-PVLVEDTSLCFNAMGGLPGPYIKWFL--KNLKPEGLHNMLAGFSD-----KTAYAQCIFAYTEG-L
S. cerevisiae   AVAALGKGKPVFVEDTALRFDEFNGLPGAYIKWFL--KSMGLEKIVKMLEPFEN-----KNAEAVTTICFADSRG
E. coli         RHAAKVTALPAIADDSGLAVDVLGGAPGIYSARYSGEDATDQKNLQKLLETMKDVPDDQRQARFHCVLVYLRHAE

H. sapiens      SQPVRLFRGRTSGRIV-APRGCQDFGWDPCFQP-DGYEQTYAEMPKAEKNAVSHRFRALLELQEYFGSLAA
C. elegans      GKPIHVFAGKCPGQIV-APRGDTAFGWDPCFQP-DGFKETFGEMDKDVKNEISHRAKALELLKEYFQNN
S. cerevisiae   E--YHFFQGITRGKIV-PSRGPTTFGWDSIFEPFDSHGLTYAEMSKDAKNAISHRGKAFAQFKEYLYQNDF
E. coli         DPTPLVCHGSWPGVITREPAGTGGFGYDPIFFV-PSEGKTAAELTREEKSAISHRGQALKLLLDALRNG
```

Fig. 7